Microelectronics
Circuit Analysis and Design

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Chapter 1

Semiconductor Materials and Devices

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In this chapter, we will:

- Gain a basic understanding of semiconductor material properties
  - Two types of charged carriers that exist in a semiconductor
  - Two mechanisms that generate currents in a semiconductor
- Determine the properties of a pn junction
  - Ideal current–voltage characteristics of a pn junction diode
- Examine dc analysis techniques for diode circuits using various models to describe the nonlinear diode characteristics
- Develop an equivalent circuit for a diode that is used when a small, time-varying signal is applied to a diode circuit
- Gain an understanding of the properties and characteristics of a few specialized diodes
- Design a simple electronic thermometer using the temperature characteristics of a diode

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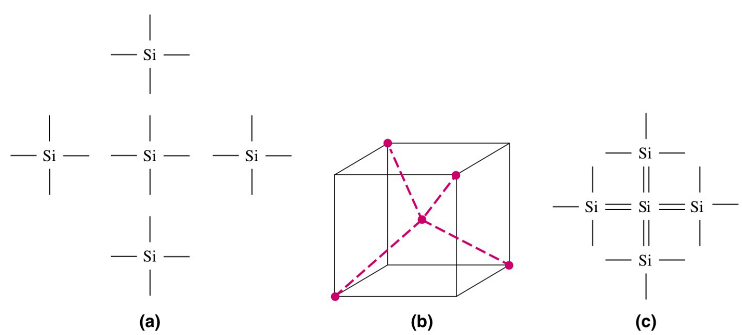
Intrinsic Semiconductors

- Ideally 100% pure material
  - Elemental semiconductors
    - Silicon (Si)
      - Most common semiconductor used today
    - Germanium (Ge)
      - First semiconductor used in p-n diodes
  - Compound semiconductors
    - Gallium Arsenide (GaAs)

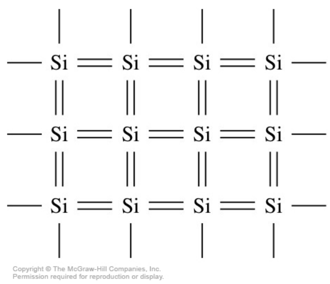
Silicon (Si)

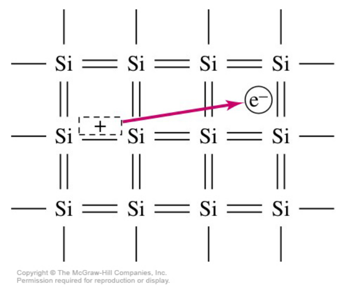


Covalent bonding of one Si atom with four other Si atoms to form tetrahedral unit cell.

Valence electrons available at edge of crystal to bond to additional Si atoms.

Effect of Temperature





At 0K, no bonds are broken.

Si is an insulator.

As temperature increases, a bond can break, releasing a valence electron and leaving a broken bond (hole).

Current can flow.

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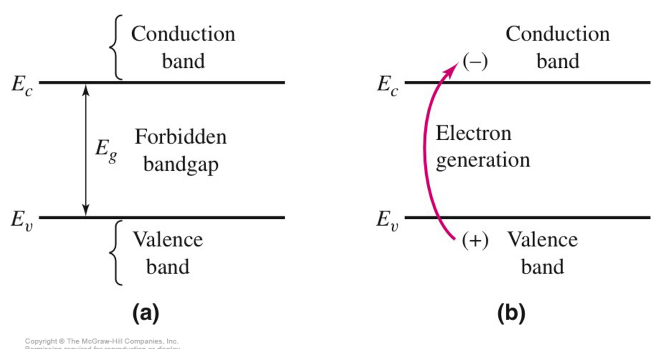
Energy Band Diagram



E_v – Maximum energy of a valence electron or hole

E_c – Minimum energy of a free electron

E_g – Energy required to break the covalent bond

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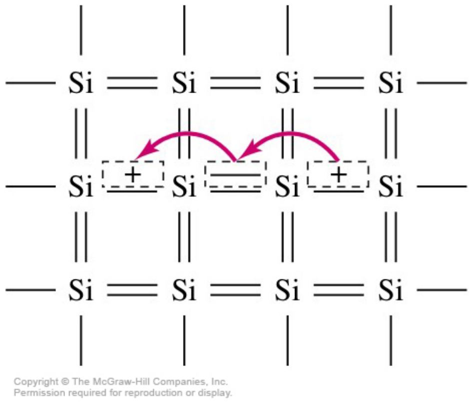
Movement of Holes



A valence electron in a nearby bond can move to fill the broken bond, making it appear as if the 'hole' shifted locations.

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Intrinsic Carrier Concentration

$$n_i = BT^{3/2} e^{\frac{-E_g}{2kT}}$$

B – coefficient related to specific semiconductor
T – temperature in Kelvin
E_g – semiconductor bandgap energy
k – Boltzmann's constant

$$n_i(Si,300K) = 1.5x10^{10}\,cm^{-3}$$

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Extrinsic Semiconductors

- Impurity atoms replace some of the atoms in crystal
  - Column V atoms in Si are called donor impurities.
  - Column III in Si atoms are called acceptor impurities.

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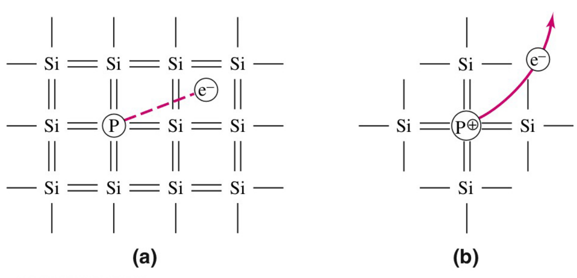
Phosphorous – Donor Impurity in Si



Phosphorous (P) replaces a Si atom and forms four covalent bonds with other Si atoms.

The **fifth** outer shell electron of P is easily freed to become a conduction band electron, adding to the number of electrons available to conduct current.

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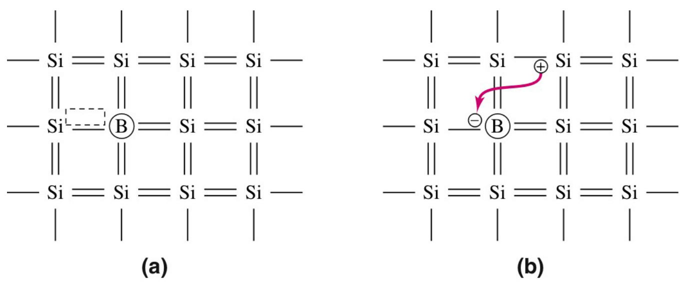
Boron – Acceptor Impurity in Si



Boron (B) replaces a Si atom and forms only **three** covalent bonds with other Si atoms.

The missing covalent bond is a hole, which can begin to move through the crystal when a valence electron from another Si atom is taken to form the fourth B-Si bond.

Electron and Hole Concentrations

n = electron concentration
p = hole concentration

$$n_i^2 = n \cdot p$$

n-type:

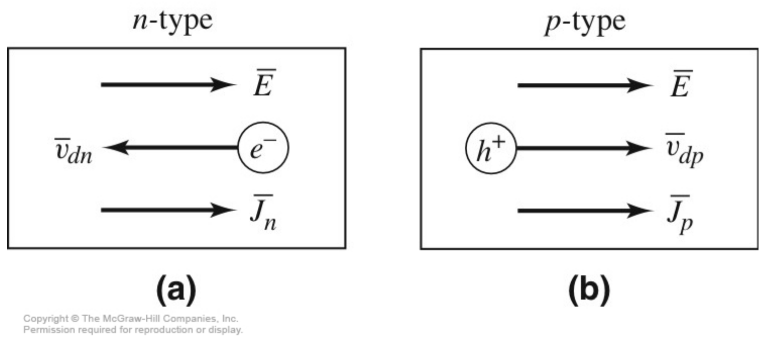
n = N_D, the donor concentration

$$p = n_i^2 / N_D$$

p-type:
p = N_A, the acceptor concentration

$$n = n_i^2 / N_A$$

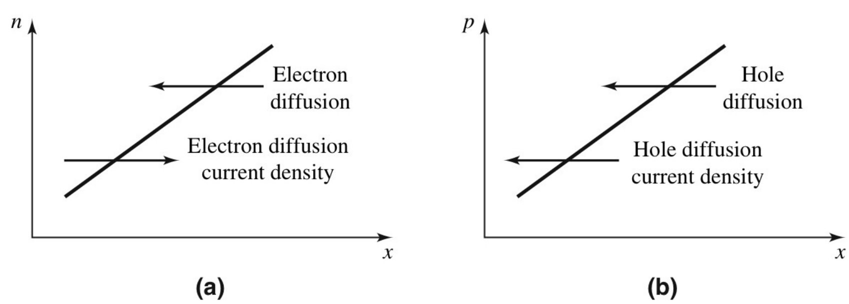
Drift Currents



Electrons and hole flow in opposite directions when under the influence of an electric field at different velocities.

The drift currents associated with the electrons and holes are in the same direction.

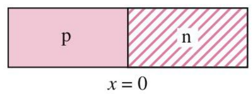
Diffusion Currents



Both electrons and holes flow from high concentration to low.

The diffusion current associated with the electrons flows in the opposite direction when compared to that of the holes.

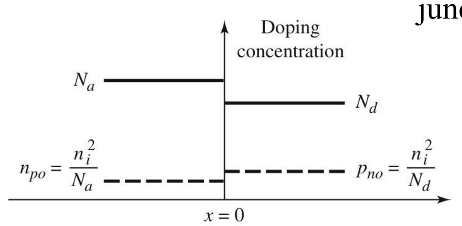
p-n Junctions



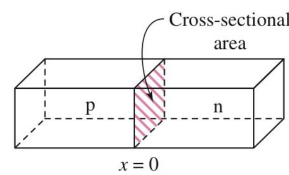
(a)

A simplified 1-D sketch of a p-n junction (a) has a doping profile (b).

The 3-D representation (c) shows the cross sectional area of the junction.

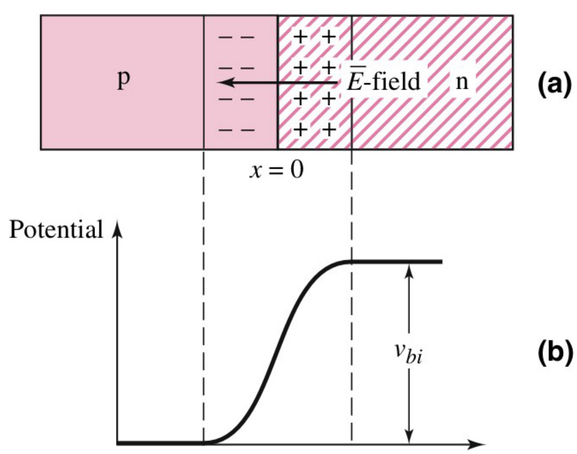


(b)



(c)

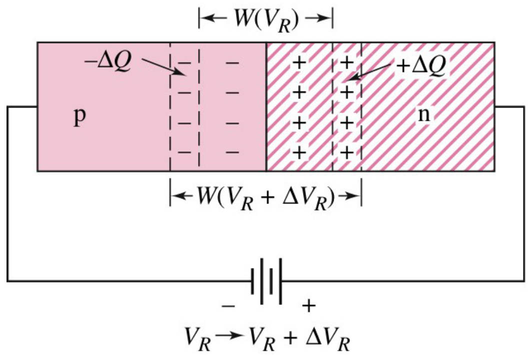
Built-in Potential



This movement of carriers creates a space charge or depletion region with an induced electric field near x = 0.

A potential voltage, v_{bi}, is developed across the junction.

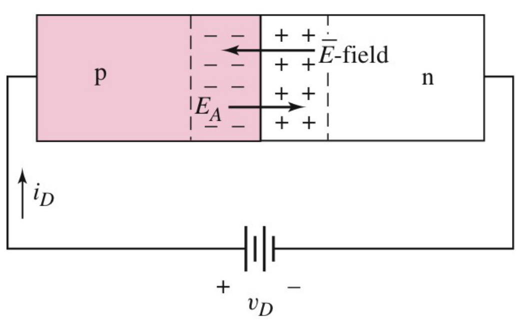
Reverse Bias



Increase in space-charge width, W, as V_R increases to $V_R+\Delta V_R$.

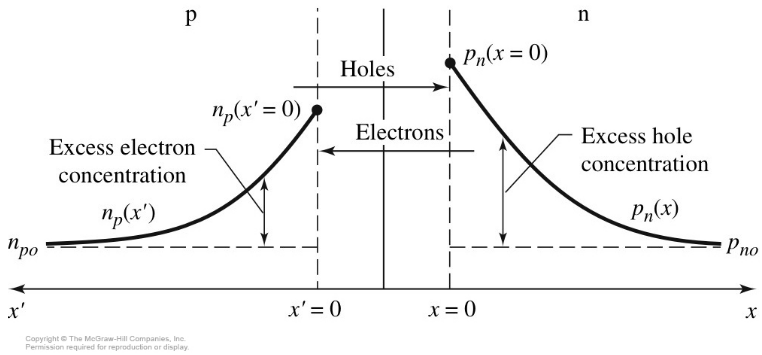
Creation of more fixed charges ($-\Delta Q$ and $+\Delta Q$) leads to junction capacitance.

Forward Biased p-n Junction



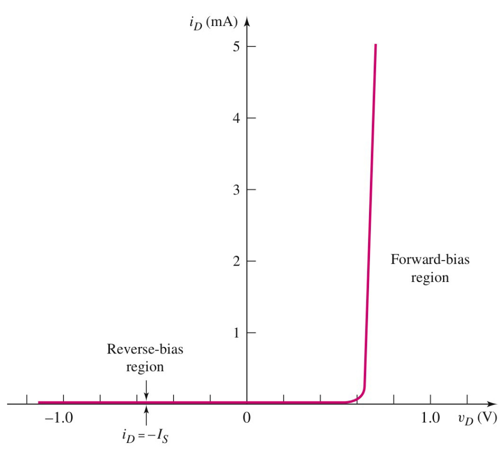
Applied voltage, v_D, induces an electric field, E_A, in the opposite direction as the original space-charge electric field, resulting in a smaller net electric field and smaller barrier between n and p regions.

Minority Carrier Concentrations



Gradients in minority carrier concentration generates diffusion currents in diode when forward biased.

Ideal Current-Voltage (I-V) Characteristics



The p-n junction only conducts significant current in the forward-bias region.

i_D is an exponential function in this region.

Essentially no current flows in reverse bias.

Ideal Diode Equation

A fit to the I-V characteristics of a diode yields the following equation, known as the ideal diode equation:

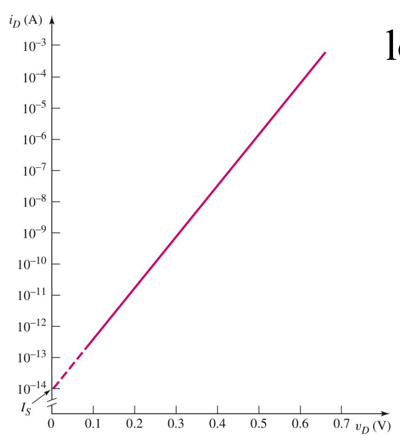
$$I_D = I_s(e^{\frac{qv_D}{nkT}} - 1)$$

kT/q is also known as the thermal voltage, V_T.

V_T = 25.9 mV when T = 300K, room temperature.

$$I_D = I_s(e^{\frac{v_D}{V_T}} - 1)$$

Ideal Diode Equation



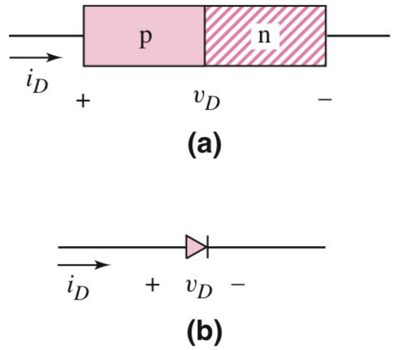
$$\log(i_D) \approx \frac{\log e}{nV_T} v_D + \log(I_s)$$

The y intercept is equal to I_S.

The slope is proportional to 1/n.

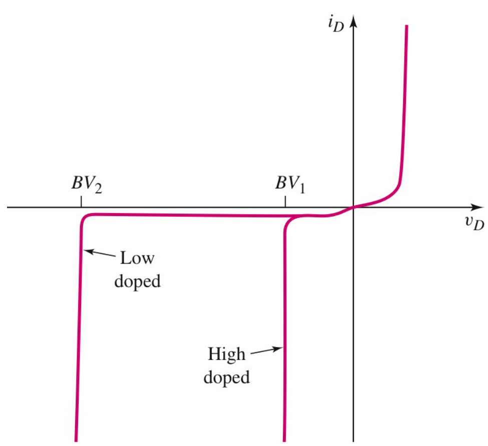
When n = 1, i_D increased by ~ one order of magnitude for every 60-mV increase in v_D.

Circuit Symbol



Conventional current direction and polarity of voltage drop is shown

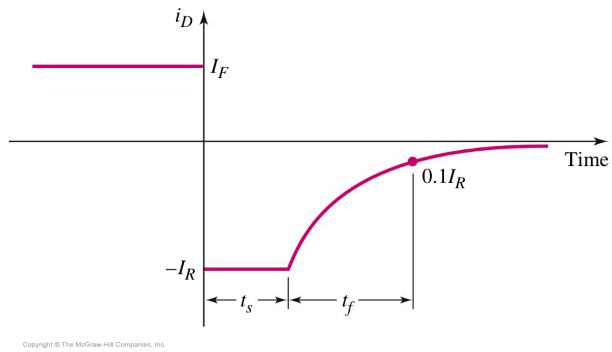
Breakdown Voltage



The magnitude of the breakdown voltage (BV) is smaller for heavily doped diodes as compared to more lightly doped diodes.

Current through a diode increases rapidly once breakdown has occurred.

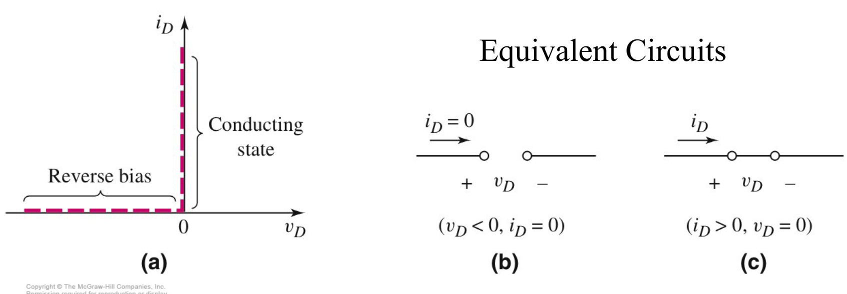
Transient Response



Short reverse-going current pulse flows when the diode is switched from forward bias to zero or reverse bias as the excess minority carriers are removed.

It is composed of a storage time, t_s, and a fall time, t_f.

dc Model of Ideal Diode

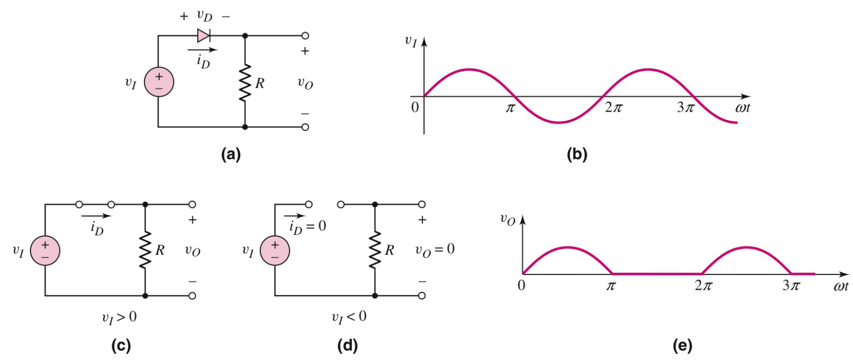


Assumes $v_{bi} = 0$.

No current flows when reverse biased (b).

No internal resistance to limit current when forward biased (c).

Half-Wave Diode Rectifier



Diode only allows current to flow through the resistor when $v_I \geq 0V$. Forward-bias equivalent circuit is used to determine v_O under this condition.

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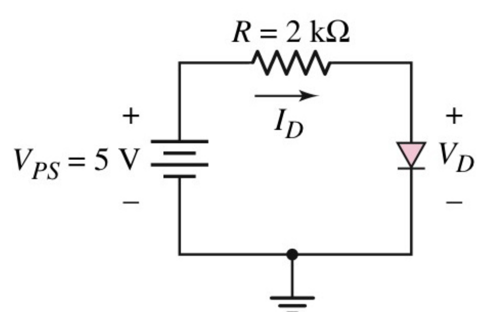
Graphical Analysis Technique



Simple diode circuit where I_D and V_D are not known.

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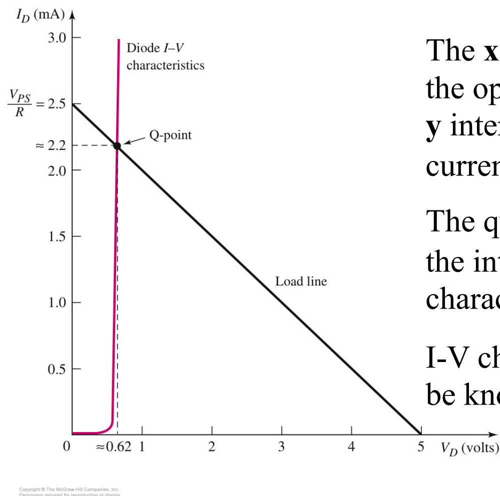
Load Line Analysis

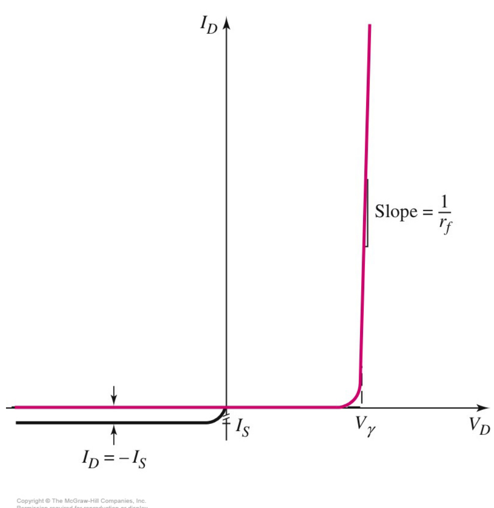


The **x** intercept of the load line is the open circuit voltage and the **y** intercept is the short circuit current.

The quiescent point or Q-point is the intersection of diode I-V characteristic with the load line.

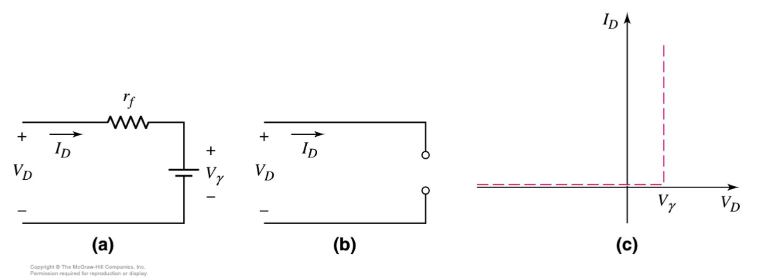
I-V characteristics of diode must be known.

Piecewise Linear Model



Two linear approximations are used to form piecewise linear model of diode.

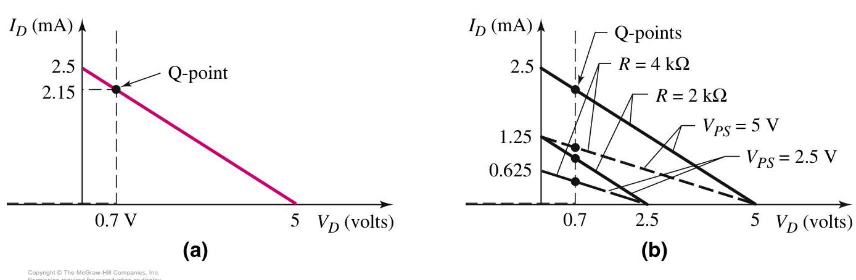
Diode Piecewise Equivalent Circuit



The diode is replaced by a battery with voltage, V_γ, with a a resistor, r_f, in series when in the 'on' condition (a) and is replaced by an open when in the 'off' condition, $V_D < V_\gamma$.

If $r_f = 0$, $V_D = V_\gamma$ when the diode is conducting.

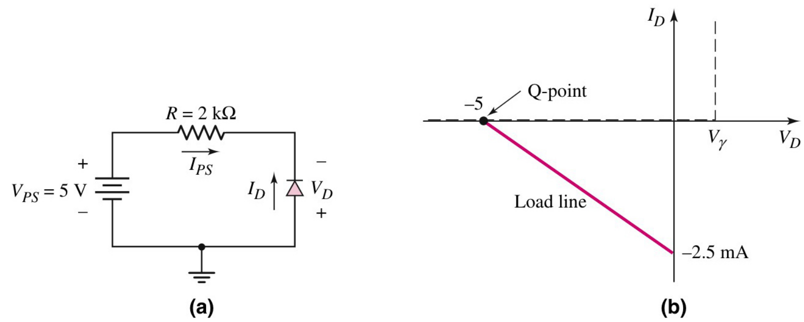
Q-point



The **x** intercept of the load line is the open circuit voltage and the **y** intercept is the short circuit current.

The Q-point is dependent on the power supply voltage and the resistance of the rest of the circuit as well as on the diode I-V characteristics.

Load Line: Reverse Biased Diode



The Q-point is always $I_D = 0$ and V_D = the open circuit voltage when using the piecewise linear equivalent circuit.

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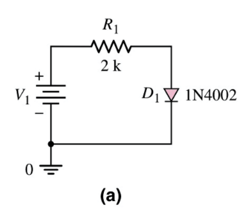
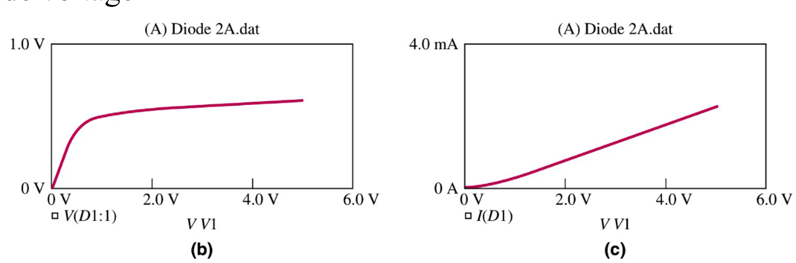
PSpice Analysis

Circuit schematic



Diode voltage

Diode current



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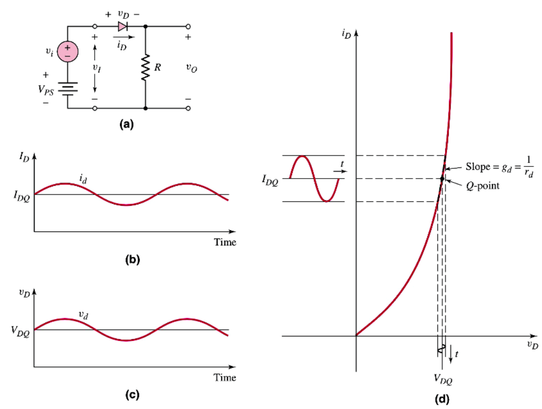
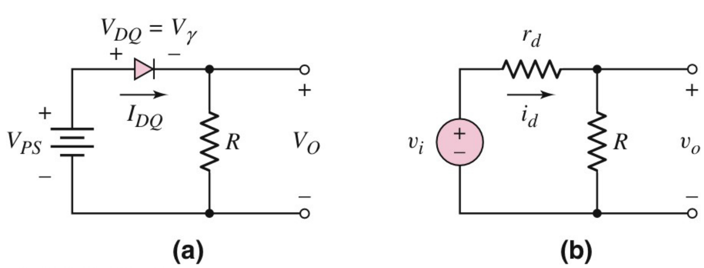
ac Circuit Analysis



Combination of dc and sinusoidal input voltages modulate the operation of the diode about the Q-point.

Equivalent Circuits

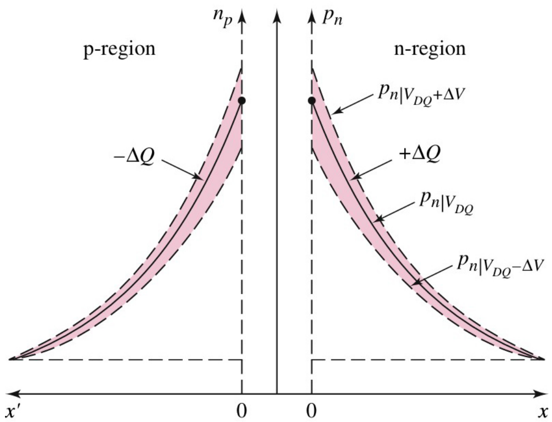


When ac signal is small, the dc operation can be decoupled from the ac operation.

First perform dc analysis using the dc equivalent circuit (a).

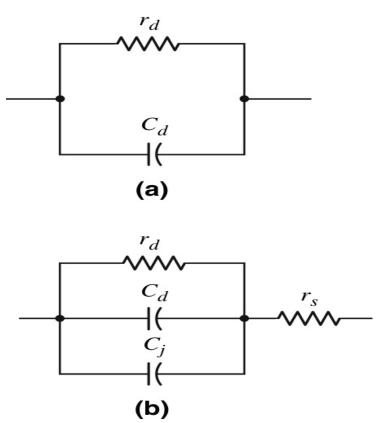
Then perform the ac analysis using the ac equivalent circuit (b).

Minority Carrier Concentration



Time-varying excess charge leads to diffusion capacitance.

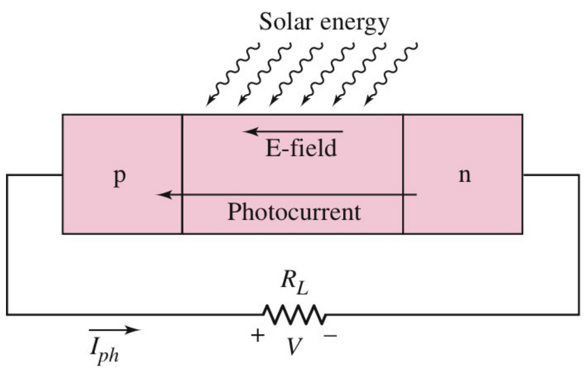
Small Signal Equivalent Model



Simplified model, which can only be used when the diode is forward biased.

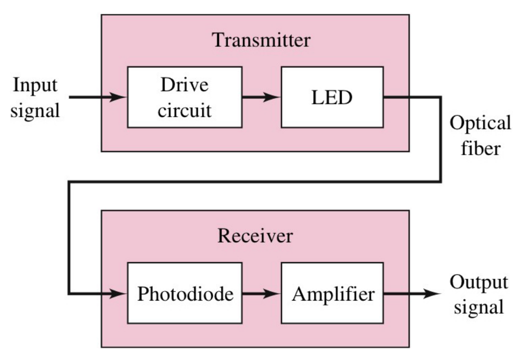
Complete model

Photogenerated Current



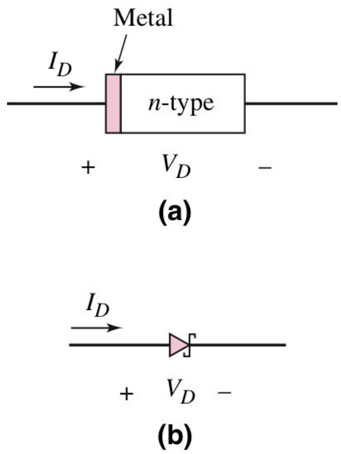
When the energy of the photons is greater than E_g, the photon's energy can be used to break covalent bonds and generate an equal number of electrons and holes to the number of photons absorbed.

Optical Transmission System



LED (**L**ight **E**mitting **Diode**) and photodiode are p-n junctions.

Schottky Barrier Diode



A metal layer replaces the p region of the diode.

Circuit symbol showing conventional current direction of current and polarity of voltage drop.

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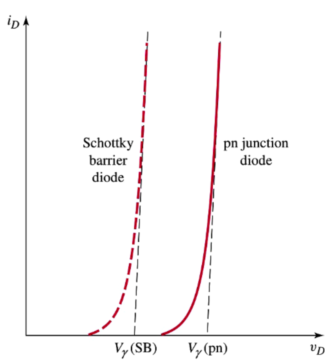
Comparison of I-V Characteristics:

Forward Bias



The built-in voltage of the Schottky barrier diode, V_γ(SB), is about ½ as large as the built-in voltage of the p-n junction diode, V_γ(pn),.

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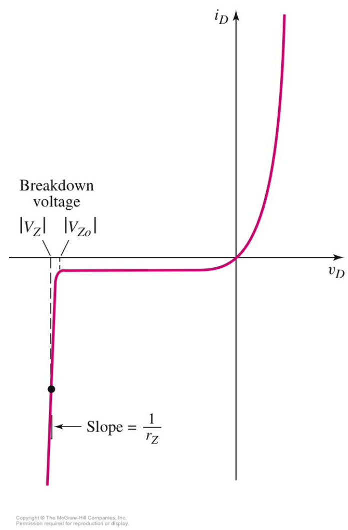
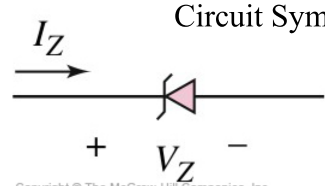
Zener Diode
I-V Characteristics



Circuit Symbol



Usually operated in reverse bias region near the breakdown or Zener voltage, V_Z.

Note the convention for current and polarity of voltage drop.

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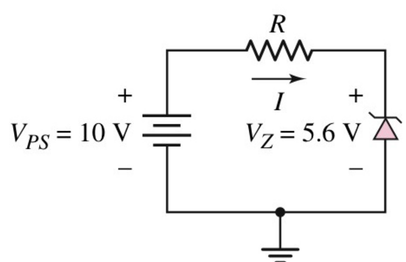
Example 1.13

Given $V_Z = 5.6V$

$r_Z = 0\Omega$

Find a value for R such that the current through the diode is limited to 3mA



$$I = \frac{V_{PS} - V_Z}{R}$$

$$R = \frac{V_{PS} - V_Z}{I} = \frac{10V - 5.6V}{3mA} = 1.47k\Omega$$

$$P_Z = I_Z V_Z = 3mA \cdot 5.6V = 1.68mW$$

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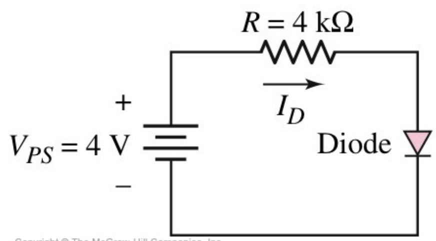
Test Your Understanding 1.15

Given V_γ (pn) = 0.7V

$V\gamma$ (SB) = 0.3V

r_f = 0Ω for both diodes

Calculate I_D in each diode.



$$I = \frac{V_{PS} - V_\gamma}{R}$$

$$I = \frac{4V - 0.7V}{4k\Omega} = 0.825mA \text{ for the p-n junction diode}$$

$$I = \frac{4V - 0.3V}{4k\Omega} = 0.925mA \text{ for the Schottky diode}$$

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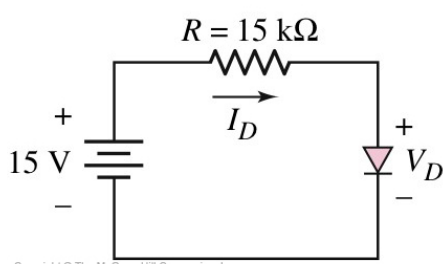
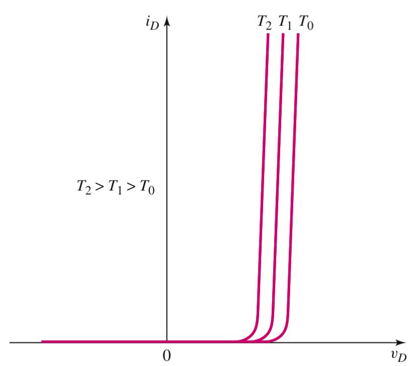
Digital Thermometer

Use the temperature dependence of the forward-bias characteristics to design a simple electronic thermometer.





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Solution

Given: $I_S = 10^{-13}$ A at T = 300K $\quad E_g/e = 1.12V$

Assume: Ideal diode equation can be simplified.

$$I_D \approx I_S e^{\frac{V_D}{V_T}} \propto n_i^2 e^{\frac{-E_g}{kT}} e^{\frac{V_D}{V_T}}$$

$$\frac{I_{D1}}{I_{D2}} = \frac{e^{\frac{-E_g}{kT_1}} e^{\frac{eV_{D1}}{kT_1}}}{e^{\frac{-E_g}{kT_2}} e^{\frac{eV_{D2}}{kT_2}}}$$

$$V_{D2} = -\frac{E_g}{e}(\frac{T_2}{T_1}) + \frac{E_g}{e} + V_{D1}(\frac{T_2}{T_1}) = 1.12(1-\frac{T_2}{T_1}) + V_{D1}(\frac{T_2}{T_1})$$

$$I_D = \frac{15V - V_D}{R} = I_S e^{\frac{V_D}{V_T}}$$

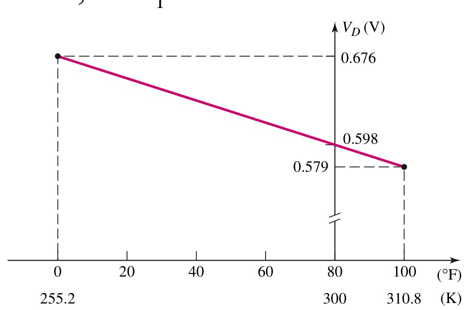
Thermometer con't

$$I_D = \frac{15V - V_D}{15x10^3\Omega} = 10^{-13} A \cdot e^{\frac{V_D}{V_T}} \quad \text{at T} = 300\text{K}$$

Through trial and error: $V_D = 0.5976V$ and $I_D = 0.960mA$

To find temperature dependence, let $T_1 = 300K$.

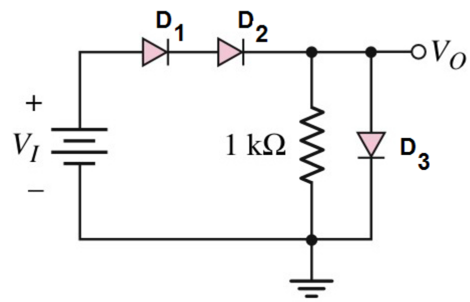
$$V_D = 1.12 - 0.522(\frac{T}{300})\ V$$



Variation on Problem 1.42 – Using the piecewise model

First, determine if the diodes are on or off. Is the open circuit voltage for each diode greater or less than $V\gamma = 0.65V$ and have the correct polarity?

$V_I = 5V$



Variation con't

a) Test what would happen if D_3 was not conducting:

If there enough voltage available to turn on D_1 and D_2?

The power supply is +5V and is attached on the p side of D_1. The n side of D_1 is attached to the p side of D_2.

So, there is sufficient voltage and with the correct polarity from the power supply to turn on both diodes.

A check to verify that both diodes are conducting – the open circuit voltage for each diode is equal to 5V, which means that the load line will intersect the conducting section of the diode's piecewise model

Variation con't

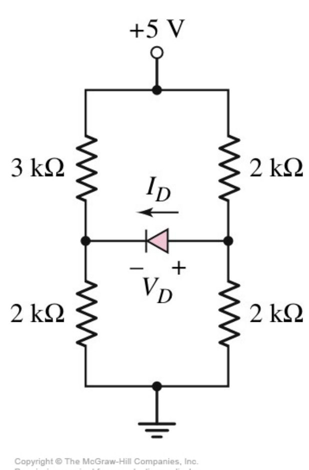
b) Next question, if current flows through the 1kΩ resistor with D_1 and D_2 on, is the voltage drop greater than or equal to Vγ?

If D_3 is open, the voltage drop across the 1kΩ resistor is:

$$V_R = 5V - 0.65V - 0.65V = 3.7V$$

Therefore, there is sufficient voltage to turn D_3 on.

Problem 1.44



First, determine if the diode is on or off. Is the open circuit voltage for the diode greater or less than Vγ?

The voltage at the node connected to the p side of the diode is

2kW 5V/(4kW) = 2.5V

The voltage at the node connected to n side of the diode is

2kW 5V/(5kW) = 2V

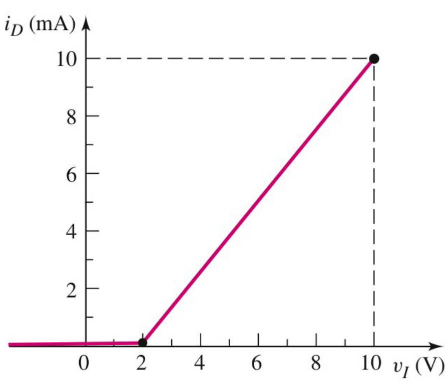
The open circuit voltage is equal to the voltage at the p side minus the voltage at the n side of the diode:

$V_{oc} = 2.5V – 2V = 0.5V.$

To turn on the diode, V_{oc} must be $\geq V_{\gamma}$.

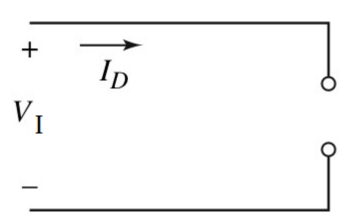
Variation on Problems

Create a piecewise model for a device that has the following I-V characteristics



Piecewise models:

$V_I < 2V, I_D = 0$

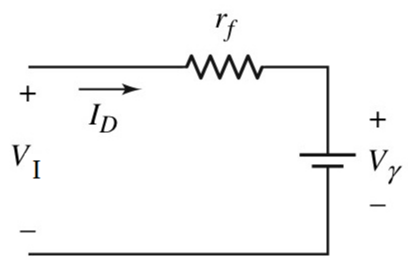


Variation con't

When $V_I \geq 2V$

$V_\gamma = 2V$

$$r_f = \frac{10V - 2V}{10mA} = 800\Omega$$



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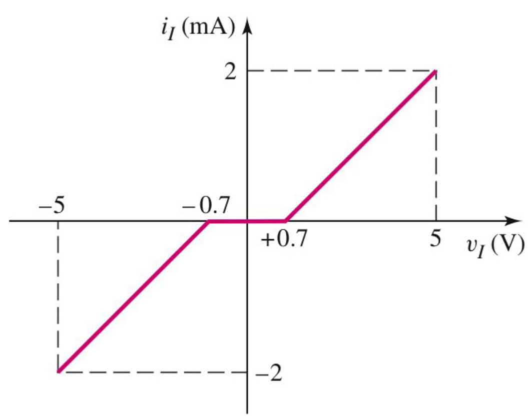
Variation on Problems



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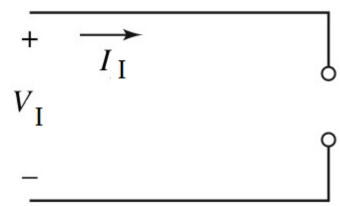
Variation con't

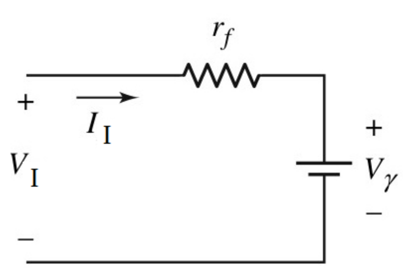
For $-0.7V < V_I < 0.7V$, $I_I = 0$



The device under test (DUT) acts like an open and can be modeled as such over this voltage range.

Variation con't

When $V_I \geq 0.7V$, I_I changes linearly with voltage

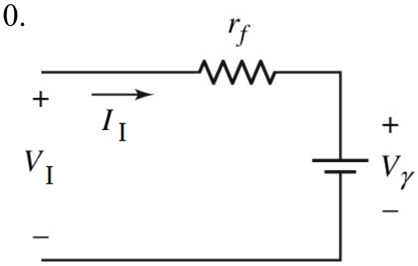


$$r_f = \frac{5V - 0.7V}{2mA} = 2.35k\Omega \text{ and } V_\gamma = 0.7V$$

Variation con't

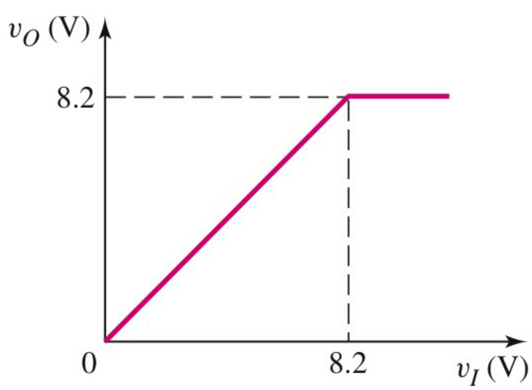
Since the I-V characteristics of the device under test (DUT) are symmetrically about $V_D = 0$, a similar model can be used for $V_I \leq - 0.7V$ as for $V_I \geq 0.7V$

For $V_I \leq - 0.$



$$r_f = \frac{5V - 0.7V}{2mA} = 2.35k\Omega \text{ and } V_\gamma = -0.7V$$

Variation on Problems



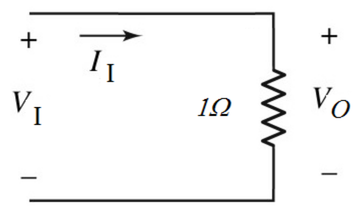
Design a circuit that has a voltage transfer function that is shown to the left.

Variation con't

For $0V \leq v_I < 8.2V$, the voltage transfer function is linear.

When $v_I = 0V$, $v_O = 0V$ so there is no need to include a battery in the piecewise linear model for this voltage range.

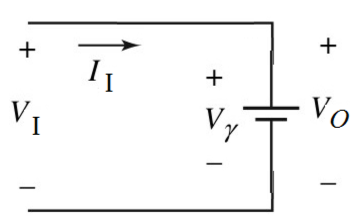
Since there is a 1:1 correspondence between v_1 and v_O, this section of the transfer function can be modeled as a 1Ω resistor.



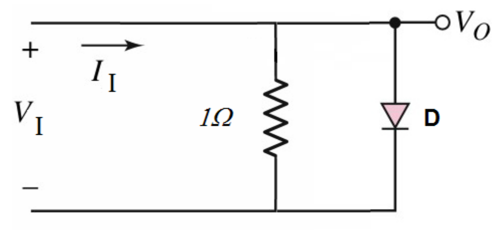
Variation con't

When $v_I \geq 8.2V$, the output voltage is pinned at 8.2V, just as if the device suddenly became a battery.

Hence, the model for this section is a battery, where $V_\gamma = 8.2V$.



Circuit



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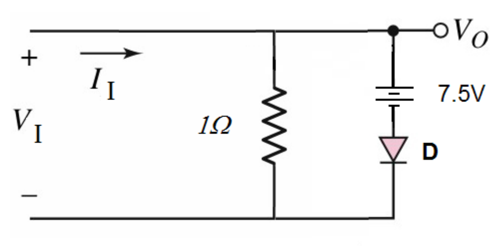
Variation con't

Or, if you assumed a more common Vγ, say of 0.7V, then the circuit would be:



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